



**Inundation, hydrodynamics, and vegetation influences
carbon dioxide concentrations in Amazon floodplain lakes**

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Key Words:	hydrological variations, aquatic plants, tropical floodplains, carbon, Amazon basin, lakes

Stephen Carpenter, Co-Editor-in-Chief - Ecosystem

RE: Amaral et al. 'Inundation, hydrodynamics, and vegetation influences carbon dioxide concentrations in Amazon floodplain lakes'

We thank the editor and reviewers for constructive comments that helped us improve the manuscript. We provide detailed responses and text showing changes requested by the subject-matter editor and the reviewers.

Subject-Matter Editor: Klement Tockner

Both reviewers agree that this is a very well done study, the data are taken with care and interpreted well. Both reviewers provide very helpful comments on how to further improve the present version of the ms. For example, the manuscript is quite lengthy and may benefit from more focus in order to make it better suitable for a general journal such as Ecosystems. Based on the recommendations of the two dedicated reviewers, I recommend minor/major revision before the ms could be considered for publication.

A: We have restructured and shortened portions of the manuscript, and added more material to supplementary materials. These changes have reduced the length of the manuscript considerably; from 11132 to 8035 words.

Reviewer: 1

General comments

The manuscript covers an important topic that I believe is well suited to publication in Ecosystems. The manuscript is clearly written with detailed descriptions of diel, seasonal and inter-annual variations of carbon dioxide concentrations and related environmental variables in various habitats of a central Amazon floodplain lake system. Three-dimensional hydrodynamic modeling was also conducted to identify diel differences in water temperature and lateral exchanges of CO₂ between plant mats and open water ecosystems. The methods and results are valuable for identifying the key processes influencing carbon dioxide dynamics in floodplain lakes, and this ms would provide a useful reference for researchers looking to study CO₂ in other lacustrine systems.

My main concern is that this paper follows a series of other articles that may have been published using subsets of the same broader dataset (Amaral et al. 2018, 2019, 2020; Barbosa et al. 2018, 2020). As such, analyses of CO₂ dynamics are somewhat limited herein, and are not as extensive as they could be had this data not already been previously published elsewhere. Hence, much of the discussion refers to findings of other studies, which is not always

well integrated with the results of the present ms. This said, I really enjoyed reading this paper, and recommend publication in Ecosystems at the editor's discretion provided that division of a broader dataset across different journals is not a major issue of concern.

A: *The material covered in the manuscript under review is different (Barbosa et al. 2018 and 2020 are about methane; Amaral et al. 2019 presents data from cruises throughout the central Amazon) or, when related (Amaral et al. 2018 and 2020), deals with different aspects. We incorporate relevant data from other studies, as appropriate. To have prepared only one paper with all the data would have been impractical and much too long.*

Specific comments

P5; L21 What is a sequence of herbaceous plants?

A: *Rephrased as, P4, L80 'As water levels rise, coverage of emergent and floating herbaceous plants expands and contracts (Junk and Piedade 1993; Engle and others 2008).'*
In the Discussion(L593-604), we describe the sequence of species, but consider these details too specific for this general introductory sentence. The two references provide further, relevant information.

P6; L2 Could add a further sentence expanding on "considerable spatial and temporal variations occur" with some values from previous studies, so as to define "considerable"

A: *We added(L98-104): 'For example, Rudorff and others (2011) reported a range from 47 to 233 μM at low water to maximum of 656 μM at high water in Lago Curuai, and Abril and others (2014) measured a range from 0.5 to 500 μM on transects in five lakes. Amaral and others (2019) sampled seven floodplain lakes along the Solimões River during four hydrological phases and reported near-surface concentrations among all the lakes to vary from 9.4 to 231 μM .'*

P7; L12 Define higher quality. Is this higher lability or other?

A: *Rephrased(L131): '...more DOC and DOC of higher quality (lability) will lead to higher CO_2 concentrations.'*

P8; L4 A legend detailing the different symbols in Figure 2 is missing.

A: *We did not include a legend on the figure, as we described each symbol in the figure caption:*
'Figure 2. Measurement dates in open water (square), flooded forest (triangle) and floating herbaceous plant (circle) habitats and water depths at open water locations in lake and embayment sites from August 2014 to September 2016. Dashed lines separate hydrological years.'

P8; L1-4/P10; L3/P11; L10 It is unclear if the marble equilibrator was used to collect grab (3+ times per day) or continuous measurements over the 24 hr

period. Clarify the methods and frequency for near-surface versus water column CO₂ measurements in the main ms or Supplementary Material.

A: *To clarify this methodological question, we modified the text as Follows(L171-176):*

'On each sampling occasion, for a given aquatic habitat investigated over a 24 h period, pCO₂ profiles were measured using an off-axis integrated-cavity output spectrometer (Ultraportable Greenhouse Gas Analyzer - UGGA, Los Gatos Research) connected to a marble-type equilibrator (Frankignoulle and others 2001), through which lake water was pumped from near-surface (0.2 to 0.3 m), and from one-meter depth intervals to within 0.5 to 1 m of the bottom.'

P8; L8 Redefine 'thermal structure'

A: *Rephrased as (L152), 'vertical profiles of temperature'.*

Further description of how these profiles were obtained is provided in the methods section of Supplementary Materials.

P10; L24 The statistical analysis section is quite long. Consider shortening this for the main body of texts by moving some of the non-critical detail to the Supplementary Material.

A: *We revised and reduced this section.*

P11; L24 Need to state R Project as the software package here or earlier.

A: *Description was inserted (Line 239) in text modified in response to previous comment.*

P13; L18/P68; Which tracer was released to the water column of concentration 1.0 (units)?

A: *The simulations are done as a numerical experiment with the 'tracer' introduced at a nominal value of 1.0 and subsequently 'diluted' by advection and dispersion. We have added actual concentrations (see description in L250-257) measured in the vegetated regions and the figures now show how values would change as a result of transport and mixing. Main text figures 6 and 7 and Figures S2 to S6 in Supplementary Material, illustrate these processes and associated modeling.*

P15, L22-25 This sentence highlights my primary concern regarding division of a dataset between multiple journals. Some of the key findings of these variations in concentrations need to be at least summarized here or in the discussion. It is a shame that I do not have institutional access to Amaral et al. (2020) to read further about these findings (likewise regarding the extended methods for CO₂ etc). Some other readers may have the same issue. Aside from this concern, the ms does read as a stand-alone article and adequately covers different aspects of the topic, so on this ground dataset division may be considered excusable.

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A: Carbon dioxide concentrations measured in the flooded forests are summarized in this paragraph, and mentioned in the context of our hydrodynamic simulations of advected sources.

Though flooded forests cover a large portion of Amazon wetlands, carbon dioxide fluxes from this environment have received limited attention. Hence, Amaral et al. (2020) dealt with this important habitat at some length, and appeared in the *Journal of Geophysical Research-Biogeosciences*, a major outlet for biogeochemical and ecosystem studies run by the American Geophysical Union and published by John Wiley & Sons. We expect the journal to be widely available.

P24; L3–P25; L4 Nice review of the literature however integration with the findings of the present study is missing. How do these rates compare to the observed diel rates of change in L. Janauacá? As with P28; L11-19.

A: The studies summarized in these two sections represent the only data on these processes available for Amazon lakes. We include them as an indication of their possible importance, but comparable data for Janauacá do not exist.

P28; L12 To the overlying what?

A: 'water' inserted (L655):

'The sediments of floodplain lakes sequester some organic carbon and release CO₂ to the overlying water as a portion of the sedimented carbon is metabolized (Smith and others 2003).'

P30; L9 Suggesting what?

A: Text inserted (L706-709):

'These values are less than most values measured in herbaceous plant mats and flooded forests, reinforcing the importance of aquatic vegetative habitats as sources of dissolved CO₂, in relation to other potential sources on the floodplain.'

P31, L15 Clarify "reduced low water levels". This could be interpreted as either reduced depths during low water levels, or less frequent low water levels.

A: Text was changed to read(L713) '...with shallower water and reductions in inundation extent ...':

P31; L10-23 The implications here need to be better articulated. In particular, the possible impacts of climate change on CO₂ concentrations and flux rates (as interpreted by the findings of this study).

A: We expanded this section (L710-L758), as suggested.

P31; L24-P32; L8 There is another hypothesis by Piedade et al. (2010; see Section 8), concerning loss of sediments following deforestation that could be integrated into this paragraph at the author's discretion. Ref: Aquatic

herbaceous plants of the Amazon floodplains: state of the art and research needed. Acta Limnol. Bras. 22(2)

A: *In the case we are describing, deforestation did not increase erosion of sediments or soils with potential impacts on the growth of herbaceous plants, as suggested in section 8 of Piedade et al. (2010). But we did mentioned this possibility (L740-L743): "These conditions would also favor loss of sediments to the river, especially in floodplain areas that are susceptible to turbulence and water currents, with the potential to affect the establishment and regrowth of herbaceous species in these areas (Piedade and others 2010)."*

Editorial suggestions

P4; L11 and 12 "the" mean concentration was...

A: *Inserted 'the'*

P4; L12 Is without one outlier necessary information in the abstract?

A: *Removed mention of one outlier.*

P4; L15 "that included"

A: *Changed, as suggested.*

P4; L19 'plant mats, open water, and...'

A: *Rephrased(L52-L55) as, 'Three-dimensional hydrodynamic modeling demonstrated that diel differences in water temperature between plant mats and open water as well as basin-scale motions caused lateral exchanges of CO₂ between vegetated habitats and open water.'*

P6; L12 (Melack and Engle 2009), 'where annual inputs...'

A: *Rephrased as (L83-L88), 'For example, an organic carbon balance for an Amazon floodplain lake by Melack and Engle (2009) found that annual inputs from the Solimões River and local runoff provided 94% of the water but only 8% of the organic carbon, while seasonal growth of floating herbaceous plants and litterfall from inundated forests contributed 72% of the organic carbon in the system.'*

P8, L10 Should the "a" in chlorophyll-a/chl-a be in italics, and C be capitalised for the abbreviation Chl-a?

A: *Revised throughout manuscript as, Chl-a*

P9, L17 ...at 0.5 m depth...

A: *Revised as suggested.*

P11; L21 ...in order to...

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4 A: *Revised as suggested.*
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6 # P13; L10 Spell out the acronym ELCOM
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8 A: *'Estuary, Lake and Coastal Ocean Model' inserted.*
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12 P14; 12 ...430 μM ...
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14 A: *' μM ' inserted.*
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17 P14; L12-15 Standardise decimal places, as well as spaces/no spaces between
18 mean and SD. Check throughout.
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20 A: *Revised accordingly.*
21

22 P14; L18 ...based on...
23

24 A: *Revised as suggested.*
25

26
27 Figure 3 Check subscript for CO_2 in legend text.
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29 A: *Subscript corrected.*
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32 P22, L20 'a significant amount...'
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34 A: *'a' added as suggested.*
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36 P23, L24 'mats'
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38 A: *Corrected spelling.*
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41 P28; L22 'relationship'
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43 A: *As a grammatical point, 'relationship' usually applies to interpersonal*
44 *interactions, while in this case 'relation' for a statistical inference would be*
45 *preferred.*
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47
48 P32; L2 'Paspalum'
49

50 A: *Spelling corrected.*
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53 Reviewer: 2
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55 Comments to the Author(s)

56 The manuscript in general is of scientific importance and fits well to the journal.
57 However, the writing and data interpretation need to be improved before
58 acceptance.
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A: *We followed suggestions made by the reviewer regarding manuscript re-organization. We revised the methods section, created topics to better organize the results and discussion sections, and have shortened the manuscript.*

Introduction

The authors used 'we' frequently. For example, page 6 Line 9 and 23, and page 7 Line 6. I suggest to avoiding this phrasing throughout the text, only if it is necessary.

A: *Most uses of 'we' were rephrased without 'we', as suggested.*

Add recent references to Premke et al. 2016 and Kayler et al. 2019.

A: *We added the references to the introduction(L66-67):
'Carbon cycling in lakes integrates inputs from the landscape and biogeochemical and ecological processes within the lakes (Tranvik and others 2009; Premke and others 2016; Kayler and others 2019)'.*

Page 3 Line 17: ... "ideal system in which examine the role of"... rephrase

A: *Rephrased (L75-L78):*

'Among river systems, the Amazon basin, with extensive floodplains and numerous lakes (Sippel and others 1992; Hess and others 2015), provides an ideal system to examine the role of floodable lands within the context of the active pipe hypothesis'.

Page 4 Line 9: ...examined...

A: *Rephrasing (L115) eliminated need for correction.*

Methods

The authors often cite unnecessary references, most of them are their own work in this subsection. Please explain your methods clearly so that the readers do not have to read all your articles to understand what has been done. Indeed, the authors explained the methods in the text and sometimes in supporting information. So these self-citations are redundant and can be removed.

I show a few examples here: page 8 Line 20-21, I am not sure why I should read your other papers in order to figure out the specifications of the sensors; page 9 Line 18, 'Analysis methods are provided in Amaral and others (2018; 2020); a short description is provided in Supplementary Material', the authors already provided the description of methods in Supplementary Material, but they cited their own articles again. Similarly, page 10 Line 7-8 and Line 21-22.

A: *We revised and shortened the methods section and expanded the Supplementary Materials to include a more complete description of the methods extracted from our earlier publications.*

Page 10 Line 10: the authors forgot to consider atmospheric pressure when calculating pCO₂. All the pCO₂ data should be recalculated.

The Janauacá floodplain is at 37 m above sea level, and we used a value of 1 atm in our calculations of $p\text{CO}_2$. Variations of atmospheric pressure measured over 2 years in a meteorological station in Manaus (34 km from our study site) averaged of 1012Mb with a CV of only 0.2%. Therefore, any variations in atmospheric pressure during our measurements would result in negligible differences. The text was revised to state(L177):

‘Dissolved CO_2 concentrations were computed from $p\text{CO}_2$ in μatm (at atmospheric pressure of 1 atm) using Henry’s constant computed from water temperature.’

Page 11 Line 6: ...examined...

A: *Corrected.*

Page 11 Line 14: What about CO_2 flux to the atmosphere? This term is missing.

A: *The mixing term includes the depth of active mixing and wind speed, two variables that influence the gas transfer velocity (k). CO_2 flux depends on k and the CO_2 concentration gradient between the water and atmosphere. Since the analysis is designed to examine factors influencing CO_2 concentrations in the water, we cannot have CO_2 flux as one of the terms in the equation. Instead, we include physical factors related to CO_2 flux.*

Results

The results section should be better structured. I suggest the authors to reorganize and put relevant results to 3 or 4 sub-sections with subtitles clearly listed. I cannot see clear logic connections in the present manner.

A: *We selected four topics, each with titled subsections, to subdivide and organize the results:*

1-Temporal and spatial differences in CO_2 concentrations

2- Temporal and spatial differences in environmental conditions

3- Hydrodynamic simulations

4- Integration of CO_2 patterns with environmental conditions

Page 14 Lines 20-22: "...probably due to the decomposition of herbaceous plants that grew during the previous low water period." Should be part of the discussion.

A: *We rephrased slightly (L279-L2282), but kept the text in results, since we observed such decay when we were in the field, and it gives context for the high value:*

‘During February 2016, an especially high water-column CO_2 concentration was obtained ($485 \mu\text{M}$), that coincided with the decomposition of herbaceous plants that grew during the previous low water period.’

Page 15 Line 2-3: ‘...water ($245 \pm 46 \mu\text{M}$) were significantly higher than values

during low ($11\pm13\mu\text{M}$), rising ($146\pm71\mu\text{M}$) and falling water ($190\pm55\mu\text{M}$) (Table 1).’ Above in Line 1 you write “ $157\pm 91 \mu\text{M}$ ”, please keep the writing with or without space consistent.

A: *Corrected accordingly and revised throughout the manuscript.*

Page 15 Line 22-25: I am surprised that the authors cited their recent paper in results. Results should only include original data that has not been published.

A: *We include results for flooded forests which were recalculated from Amaral et al. (2020) as depth averages, hence, need to cite that paper.*

Page 17 Line 3: between ‘years’.

A: *Corrected.*

Page 17 Line 22, 23, 24: what are OL site and EM site? Please explain.

A: *These were abbreviations for open lake and embayment, respectively. We now use the full names.*

Page 19 Line 15: ‘Hydrodynamic simulations’. The authors were able to tell there were lateral exchanges that shaped the pCO_2 depth profiles in water column, can you please show how much? Quantitative estimations would be more valuable.

A: *We changed relative tracer values to CO_2 concentrations representative of conditions in macrophyte mats and fringing forests and explained how the dissolved gas would be advected and diluted by physical processes, and illustrated the concentrations in a series of figures (Fig. 6-7; Figure S4 and Supplementary Materials).*

Page 20 Line 7-9: you should not cite another paper in your results, please move it to the discussion if needed.

A: *This citation to current speeds reported by Doyle (1991) is better suited to the results than discussion.*

Page 20 Line 15: (see Supplementary Materials). Which figure/table or text? Please specify.

A: *Fig. 7; Fig. S6 added (L441).*

Discussion

Also this part should be better organized, the current version is a combination of discussion, literature review and conclusions. In addition, it is kind of hard to follow with a clear logical guidance, it can be much improved if dividing it into subsections. Personally, I would also prefer a more concise text (11 pages of discussion is quite extensive) as the whole manuscript is already a bit lengthy.

In the conclusions the 6 major points of the study are nicely given. Accordingly, I would expect to see the same structure in the discussion and more focused on these major points!

A: *Subtitles added to organize topics:*

- 1- *Herbaceous plants as a source of CO₂ to open waters in floodplain lakes*
- 2- *Interannual variations of herbaceous plants and impacts on CO₂ concentrations*
- 3- *Variations in environmental conditions, their impact on CO₂ concentrations and alternative sources of CO₂ in floodplain lakes*
- 4- *Implications associated with environmental changes*

Deleted subsection called 'Comparisons to other studies', and summarized limited relevant material in introduction.

Page 22 Line 17: ...'based on relevant literature'..., please refer to the respective literature!

A: *The literature relevant to the discussion is included in the subsequent sections.*

Page 28 Line 2-3: ...'lake site .' Please remove the space between "site" and the dot in Line 3.

A: *Corrected.*

Page 28 Line 11-20: this paragraph can go to introduction. It is purely a literature review.

A: *The information extracted from references supports the points in the discussion and would be out of context in the introduction.*

Page 32 Line 18: can you please take conclusions out and make it an individual section?

A: *A separate section with conclusions is identified.*

Page 32 Line 18-19: 'Our study was the first to examine vertical profiles of CO₂ over diel and seasonal scales'. I am not sure if this is really the case. You might be the first who look at it in Amazon floodplain lakes.?

A: *Sentence removed.*

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Inundation, hydrodynamics, and vegetation influence carbon dioxide concentrations in Amazon floodplain lakes

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Author Contributions¹

Title shortened version: CO₂ concentrations in floodplain lakes

Model and Data Archiving: link to repository in preparation

¹ Author contributions: JHFA: Lead author, conceived research, performed field sampling, performed sample and data analysis, wrote paper. PMB, JMM, BRF, AVB, SM: conceived research, wrote paper. DK, PMB performed field sampling and sample analysis, performed data analysis wrote paper. SM, AC, WZ: performed data analysis, contributed models, wrote paper. All authors critically revised the manuscript and approved the final submission.

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Manuscript Highlights

- 1- Aquatic plants are major sources of CO₂ to open waters of floodplain lakes.
- 2- Extended low-water period enhanced CO₂ concentrations as inundated plants decayed.
- 3- Diel changes in thermal gradients drive lateral exchange of CO₂.

Abstract

Extensive floodplains and numerous lakes in the Amazon basin are well suited to examine the role of floodable lands within the context of the sources and processing of carbon within inland waters. We measured diel, seasonal and inter-annual variations of CO₂ concentrations and related environmental variables in open water and flooded vegetation, and estimated their habitat area using remote sensing in a representative Amazon floodplain lake, Lake Janauacá. Variability in CO₂ concentrations in open water resulted from changes in the extent of inundation and exchange with vegetated habitats. Depth-averaged values of CO₂ in the open water of the lake, $157 \pm 91 \mu\text{M}$ (mean $\pm$ SD), were less than those in an embayment near aquatic vegetation, $285 \pm 116 \mu\text{M}$, and were variable over 24-h periods at both sites. Within floating herbaceous plant mats, the mean concentration was $275 \pm 77 \mu\text{M}$, while in flooded forests it was $217 \pm 78 \mu\text{M}$. The best statistical model, that included CO₂ in aquatic plant mats, water clarity, rate of change in water level and chlorophyll-*a* concentrations, explained around 90% of the variability in CO₂ concentration. Three-dimensional hydrodynamic modeling demonstrated that diel differences in water temperature between plant mats and open water as well as basin-scale motions caused lateral exchanges of CO₂ between

vegetated habitats and open water. Our findings extend understanding of CO₂ in tropical lakes and floodplains with measurements and models that emphasize the importance of flooded forests and aquatic herbaceous plants fringing floodplain lakes as sources of CO₂ to open waters.

Key Words: Amazon basin, carbon, tropical floodplains, aquatic plants, hydrological variations

Introduction

Carbon cycling in lakes integrates inputs from the landscape and biogeochemical and ecological processes within lakes (Tranvik and others 2009; Premke and others 2016; Kayler and others 2019). As a component of the active pipe hypothesis, lakes contribute to the processing, storing and emissions of carbon en route to oceans (Cole and others 2007). Carbon inputs from vegetated areas within the aquatic ecosystems can alter regional carbon balances (Amaral and others 2020; Drake and others 2018). Floodplain lakes, abundant in tropical and northern regions, receive organic and inorganic carbon from their catchments and from areas with submerged, floating and emergent plants.

Among river systems, the Amazon basin, with extensive floodplains and numerous lakes (Sippel and others 1992; Hess and others 2015), provides an ideal system to examine the role of floodable lands within the context of the active pipe hypothesis. Large seasonal and inter-annual variations in depth and extent of inundation create a seasonally flooded region called the aquatic-

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3 80 terrestrial transition zone (Junk and others 1989). As water levels rise, coverage
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5 81 of emergent and floating herbaceous plants expands and contracts (Junk and
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7 82 Piedade 1993; Engle and others 2008), fringing forests are inundated (Junk and
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9 83 others 2010), and open water areas expand. For example, an organic carbon
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11 84 balance for an Amazon floodplain lake by Melack and Engle (2009) found that
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13 85 annual inputs from the Solimões River and local runoff provided 94% of the
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15 86 water but only 8% of the organic carbon, while seasonal growth of floating
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17 87 herbaceous plants and litterfall from inundated forests contributed 72% of the
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19 88 organic carbon in the system. Others have inferred the influence of aquatic
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21 89 vegetation on CO₂ concentrations based on higher concentrations near
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23 90 vegetated lake margins (Rudorff and others 2011) and in lakes with a larger
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25 91 percentage of vegetated floodplain (Abril and others 2014). Abril and Borges
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27 92 (2019) suggest that riparian and littoral wetlands have strong hydrological
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29 93 connectivity to inland waters and often are productive, assimilating atmospheric
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31 94 CO₂ and transferring a portion of the fixed carbon to the water.
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37 95 As is common in lakes throughout the world (Sobek and others 2005;
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39 96 Marotta and others 2009; McDonald and others 2013), Amazon lakes are often
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41 97 supersaturated in carbon dioxide with respect to atmospheric equilibrium,
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43 98 though considerable spatial and temporal variations occur. For example,
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45 99 Rudorff and others (2011) reported a range from 47 to 233 µM at low water to
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47 100 maximum of 656 µM at high water in Lago Curuai, and Abril and others (2014)
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49 101 measured a range from 0.5 to 500 µM on transects in five lakes. Amaral and
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51 102 others (2019) sampled seven floodplain lakes along the Solimões River during
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53 103 four hydrological phases and reported near-surface concentrations among all
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55 104 the lakes to vary from 9.4 to 231 µM. All these data are from near-surface, open
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water habitats during daytime, and not from vegetated habitats or over diel periods. The variations in dissolved CO₂ are likely associated with biological and physical factors including aquatic plants and algal primary production (Engle and others 2008; Forsberg and others 2017a) and respiration (Amaral and others 2018), dissolved organic carbon (DOC) and its susceptibility to degradation (Ward and others 2013), inundation extent (Abril and others 2014) and watershed inputs (Johnson and others 2008). Variations in meteorological conditions, thermal stratification and mixing, exchange with the atmosphere, and lateral advection (MacIntyre and others 2019) can also contribute to variability in CO₂ concentrations.

To examine temporal and spatial variations in dissolved CO₂ in Amazon floodplain lakes and the physical and biological processes likely to influence these variations, we measured diel, seasonal and inter-annual variations of dissolved CO₂, and related environmental variables combined with remote sensing of flooded vegetation in a representative central Amazon floodplain lake, Lake Janauacá. The Janauacá floodplain has a large open water area close to the Solimões River and numerous embayments in close proximity to vegetated habitats. As is typical of central Amazon floodplains, the open waters are surrounded by aquatic-terrestrial transition zones with trees and herbaceous plants (Fig. 1).

A statistical model of factors influencing variations in dissolved CO₂ concentrations was developed to evaluate the importance of inundation, vegetated habitats, planktonic productivity, DOC and hydrodynamics. Specifically, we expect: 1) CO₂ concentrations to vary seasonally and to increase as water depths and extent of inundation increase; 2) CO₂

concentrations in open water areas are influenced by vegetative habitats; and
3) more DOC and DOC of higher quality (lability) will lead to higher CO₂
concentrations. To further examine exchanges between vegetated areas and
open waters, a 3-dimensional hydrodynamic model was adapted to conditions
on the floodplain. The results of our study contribute to understanding of
controls of CO₂ concentrations in inland waters.

Methods

Study sites: Measurements were made in two parts of Lake Janauacá
that differed in wind exposure, stratification and proximity of the open water to
vegetated habitats: open lake (3°22.6' S, 60°15.2' W) and an embayment
(3°24.4' S, 60°14.8' W) (Fig. 1). Further description of the Janauacá floodplain
is provided in Bonnet and others (2017), Amaral and others (2018; 2020) and in
Supplementary Material.

Environmental measurements: Sampling started near sunrise (~ 6 am)
and was conducted at 4 to 6 h intervals with each site sampled at least three
times over a 24 h period. At each site, open water was present at all times, and
the presence and areal extent of floating plants and flooded forest habitats
varied seasonally (Fig. 2). Measurements of carbon dioxide partial pressure
(pCO₂), together with environmental parameters including meteorological
variables (wind speed and direction, relative humidity, photosynthetically
available radiation (PAR) and air temperature), Secchi disk visibility and
underwater profiles of PAR (indications of water clarity), vertical profiles of
temperature and dissolved oxygen (DO), electrical conductance, pH, dissolved
organic carbon (DOC), indices of colored dissolved organic matter (CDOM),

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3 155 chlorophyll-*a* (Chl-*a*), total nitrogen (TN), total phosphorus (TP) and total
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5 156 suspended sediments (TSS), were made on twenty occasions between August
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7 157 2014 and September 2016, representing two hydrological years. Water for Chl-
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9 158 *a*, DOC, CDOM, TSS, TN and TP analyses was collected at both stations from
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11
12 159 0.5 m depth. CDOM indices include specific absorbance at 350 nm (a_{350}),
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14 160 ultraviolet absorbance at 254 nm (SUVA) and the slope ratio (SR). SUVA is
15
16 161 negatively associated with microbial degradation and discriminates between
17
18 162 labile and refractory DOC (Hansen and others 2016). SR is inversely related to
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20 163 DOC molecular weight and higher values represent proportionally more low
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22 164 molecular weight compounds (Helms and others 2008). The depth of active
23
24 165 mixing was estimated as the depth from the near-surface temperature to the
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26 166 depth with an increase in temperature of 0.02°C. Daily measurements of water
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28 167 levels, obtained from manual readings at two altimetric-referenced stage
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30 168 gauges (Bonnet and others 2017), were used to estimate ΔZ , which was the
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32 169 water level change over the 10 days before each sampling period.
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34 170 Methodological details are provided in Supplementary Materials.
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40 171 On each sampling occasion, for a given aquatic habitat investigated over
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42 172 a 24 h period, $p\text{CO}_2$ profiles were measured using an off-axis integrated-cavity
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44 173 output spectrometer (Ultraportable Greenhouse Gas Analyzer - UGGA, Los
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46 174 Gatos Research) connected to a marble-type equilibrator (Frankignoulle and
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48 175 others 2001), through which lake water was pumped from near-surface (0.2 to
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50 176 0.3 m), and from one-meter depth intervals to within 0.5 to 1 m of the bottom.
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52 177 Dissolved CO_2 concentrations were computed from $p\text{CO}_2$ in μatm (at
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54 178 atmospheric pressure of 1 atm) using Henry's constant computed from water
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3 179 temperature. Water-column concentrations were calculated by averaging the
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5 180 concentrations measured at all depths.
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8 181 Herbaceous plant areas for the northern portion of Lake Janauacá were
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10 182 estimated from satellite imagery (Fig. 1). Multispectral images (RapidEye
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12 183 Orthorectified Level 3A images acquired in August 2014, 2015 and 2016 with a
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14 184 spatial resolution of 6.5 m resampled to a 5-m grid and a high-resolution
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16 185 multispectral image (Apollo World View 2; August 2014) with 0.7 m resolution
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18 186 were used to manually classify floating plants, based on field observations and
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20 187 spectral characteristics. The high-resolution image covered an area of 25 km²
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22 188 that included the open lake and embayment sites. The areas of flooded forest
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24 189 and open water for each sampling campaign were estimated as described in
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26 190 Amaral and others (2020) and were used to calculate the ratio between open
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28 191 water and inundated forest areas.
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33 192 *Statistical analysis:* We adopted a multiple-level statistical approach to
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35 193 analyze spatial variability of CO₂ concentrations at different temporal scales and
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37 194 in relation to environmental and landscape variables. First, we analyzed the
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39 195 overall differences in CO₂ concentrations between the embayment and lake
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41 196 sites, as well as changes per site in water-column concentrations at diel,
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43 197 seasonal and inter-annual scales. We compared concentrations between sites
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45 198 and day-night differences with paired t tests, and by one-way ANOVA when
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47 199 comparing more than one sampling campaign or hydrological period. We used
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49 200 two-way ANOVA to test differences between hydrological periods among
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51 201 different years. We used Tukey's HSD as a post hoc procedure that corrects
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53 202 alpha for multiple comparisons without losing statistical power.
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Second, we calculated water-column CO₂ concentrations per campaign and per site to compare with environmental and landscape variables, averaged, if necessary, to obtain daily values. We grouped variables by terms expected to influence CO₂ concentrations:

$$Eq\ 1: CO_2 = \alpha \pm \beta_1 \text{inundation} \pm \beta_2 \text{productivity} \pm \beta_3 \text{DOC} \pm \beta_4 \text{mixing} \pm \beta_5 \text{other}$$

The term called inundation includes the variables ΔZ , and the open water to flooded forest area ratio. The productivity term includes near-surface CO₂ concentration in herbaceous plant mats, Chl-*a*, nutrients (TN and TP), and light-related variables (Secchi depth, TSS and underwater attenuation of PAR). The DOC term includes the DOC concentration and its optical properties represented by SUVA, SR, and a_{350} . The mixing term includes the depth of active mixing and wind speed. Finally, the term called other includes surface conductivity and temperature. As a first step, in order to select and reduce the variables to be included in the model to explain CO₂ variability, we tested the autocorrelation between variables associated with each of the terms using the *rcorr* function in the package *Hmisc*. When autocorrelation ($p < 0.05$) between variables within a term occurred, we selected the variable with best theoretical or biological explanation (see Results).

With the variables selected, we performed a further selection and averaging model procedure (Grueber and others 2011) with the goal to retain a set of models weighted by information theoretic criteria to account for model selection bias (Anderson 2008; Lukacs and others 2010). First, we used variance inflation factor analysis to identify collinear variables in the resulting model after step one, and a threshold of 5 was chosen to remove collinear

variables, representing different terms in the model, which was called full model. Response and all predictor variables in the full model were standardized using the *arm* package (Gelman and Su 2018), a step for interpreting the parameter estimates after model averaging. From this model we generated a confidence set, using the “dredge” function available in the *MuMIn* package (Barton and Barton 2018). We used the function “get.models” from the *MuMIn* package to obtain the top models within two units of DAICc of the ‘best’ model (Grueber and others 2011). As a final step we used the “model.avg” function in R to estimate parameter coefficients in the confidence set, calculating conditional values using the mean of regression coefficients weighted by the AIC weight (w_i) from each model including that variable (Gruner and others 2017). Graphs and statistical analyzes were done using GraphPad Prism Version 7.01, and in R (R Core Development Team 2020).

Hydrodynamic modeling: Modeling of the hydrodynamics of open water regions in lake and embayment was conducted using the 3-dimensional coupled Hydrodynamic-Aquatic Ecosystem Model (AEM3D) (Hodges and Dallimore 2019). AEM3D is derived from the Estuary, Lake and Coastal Ocean Model (Hodges and others 2000) and uses a z-coordinate Cartesian grid allowing non-uniform spacing in three directions and solves the unsteady Reynolds-averaged Navier-Stokes equation under the Boussinesq approximation. Details about the AEM3D numerical schemes are provided by Hodges (2000). We incorporated an additional algorithm to account for differences in heating caused by floating plants in the embayment (Woodward and others 2017). In the lake, a numerical tracer, expressed as CO_2 concentration of 250 μM , was continuously introduced through the water column

near fringing aquatic vegetation. In the embayment, a numerical tracer with CO₂ concentration of 235 µM was introduced continuously into the upper 0.3 m of water inside the mat of floating plants, where respiration is likely to be considerable. The goal was to track the mass transfer induced by wind-driven motions in the open lake and by differential heating and cooling between the floating plants and adjacent water in the embayment.

The inputs to the model include bathymetry, meteorological variables and temperature measured at the lake and water level change (as described above and in Supplementary Materials). The model was run with a 60 s time-step, 100 m × 100 m × 0.1 m grid in the lake and a 20 s time-step, 5 m × 5 m × 0.1 m grid in the embayment. We confirmed that the model simulated the diurnal stratification and nocturnal mixing in the open lake and embayment, surface temperature difference between inside and outside the floating plants in the embayment, and wind driven basin-scale motions in the open lake by comparison with time-series temperature data.

Results

Temporal and spatial differences in CO₂ concentrations

Embayment open water: CO₂ concentrations in near-surface waters of the open water in the embayment varied from 3.0 µM (low water) to 430 µM (rising water) with a mean ± standard deviation of 183 ± 97 µM (Table S1). Water-column CO₂ concentrations varied from 4.1 to 485 µM with an overall mean of 285 ± 116 µM. Water-column CO₂ concentrations measured during rising water (313 ± 89 µM) were similar to values measured during high water (351 ± 46 µM), but values from both periods were higher than concentrations

measured during falling ($226 \pm 144 \mu\text{M}$) and low water ($168 \pm 119 \mu\text{M}$) based on one-way ANOVA ($F(3,102) = 12.9$, $p < 0.001$) (Table 1). During February 2016, an especially high water-column CO_2 concentration was obtained ($485 \mu\text{M}$), that coincided with the decomposition of herbaceous plants that grew during the previous low water period.

Lake open water. In the open water of the lake, near-surface CO_2 varied from 0.2 (low water) to $280 \mu\text{M}$ (high water), with a mean of $131 \pm 83 \mu\text{M}$ (Table S1). Water-column CO_2 concentrations varied from 0.2 to $302 \mu\text{M}$ with an overall mean of $157 \pm 91 \mu\text{M}$. Water-column CO_2 concentrations during high water ($245 \pm 46 \mu\text{M}$) were significantly higher than values during low ($11 \pm 13 \mu\text{M}$), rising ($146 \pm 71 \mu\text{M}$) and falling water ($190 \pm 55 \mu\text{M}$) (Table 1). Concentrations during low water were lower than in other periods, and rising and falling water periods were different based on one-way ANOVA ($F(3,102) = 61.5$, $p < 0.001$).

Overall, CO_2 concentrations averaged through the water column were greater than the values measured near the surface (0.2 to 0.3 m) (Paired- t-test, $t=11.7$, $df=205$, $p < 0.001$) for both open water sites (Fig. 3).

CO_2 concentrations in vegetated habitats: Near-surface CO_2 varied from 8.0 to $2050 \mu\text{M}$, and CO_2 averaged water-column values from 25 to $2032 \mu\text{M}$ in herbaceous plant mats. The highest CO_2 was recorded when a *Paspalum repens* bed was decomposing during the low water in 2015 in the embayment; this value was judged an outlier and removed from further comparisons. Mean concentration (without the outlier and with both sites combined) was $240 \pm 81 \mu\text{M}$ for near-surface values and $275 \pm 77 \mu\text{M}$ for water-column CO_2 . Water-

column CO₂ values were lower during low water than other periods ($F(3,115) = 4.7$, $p=0.004$) (Table 1).

At flooded forest sites, near-surface CO₂ varied from 19 to 329 μM , and CO₂ averaged water-column values from 21 to 392 μM . Mean concentration was $155 \pm 71 \mu\text{M}$ for near-surface values and $217 \pm 78 \mu\text{M}$ for water-column CO₂. Water-column CO₂ values were higher ($257 \pm 47 \mu\text{M}$) during high water than other periods (RW= $181 \pm 60 \mu\text{M}$, FW= $201 \pm 97 \mu\text{M}$) ($F(2,72) = 7.5$, $p=0.001$). A complete description of variations in near-surface water concentrations for flooded forest sites, including diel, seasonal and inter-annual variations is given in Amaral and others (2020).

Comparison among habitats and sites: Mean near-surface CO₂ values in floating plant mats were higher than the mean values in the open water habitats: embayment ($F(3,328) = 30.6$, $p<0.001$) and open lake sites ($F(3,328) = 30.6$, $p<0.001$), respectively (Table S1). Open water values in the embayment were significantly higher than those measured in the open water of the lake (Table S1). In the embayment, open water, water-column CO₂ values were similar to those in herbaceous plant mats, and both were higher than mean concentrations measured in flooded forest habitats. Herbaceous plant and forest habitats fringing the open water of the lake had similar values, while open water had lower mean values than fringing vegetated sites ($F(5,390) = 27.6$, $p<0.001$). Water- column CO₂ values in the open water of the embayment were higher than the values measured in the same habitat in the lake ($F(5,390) = 27.6$, $p<0.001$) (Table 1).

Inter-annual differences at open water sites: Differences in water level between the two hydrological years are reflected in water-column CO₂

concentrations in open water environments (Fig. 4A). When analyzing both open water sites together, the interaction between hydrological period and sampled year is statistically significant (two-way ANOVA, water column: $F(3,198) = 10.38$; $p < 0.001$). Mean water-column CO_2 concentrations measured during the low water ($118 \pm 139 \mu\text{M}$) and rising water ($278 \pm 132 \mu\text{M}$) of year two were higher than those in year one: more than 300% for LW ($35 \pm 29 \mu\text{M}$) and 42% for RW ($195 \pm 72 \mu\text{M}$) (Fig. 4). In contrast, mean concentration measured during the falling water period of year one ($311 \pm 79 \mu\text{M}$) was 70% higher than mean concentrations measured during year two ($182 \pm 89 \mu\text{M}$), and mean high water concentrations were similar between years: Year 1 = $310 \pm 61 \mu\text{M}$ and year 2 = $292 \pm 81 \mu\text{M}$. When comparing similar hydrological periods between years, rising and falling water periods were significantly different (Tukey post hoc test, $p < 0.01$). Similar patterns between years are evident when all habitats are included (Fig. 4B).

Diel variability in CO_2 : In open water sites of the embayment and lake, water-column CO_2 concentrations were variable over 24 h periods. The coefficient of variation (CV) varied from 3% to 88% for the embayment and from 2% to 102% in the lake, and the largest CVs were, in general, associated with high chlorophyll-*a* values (Table S3). In floating plant mats at both sites, less diel variability was observed compared to the open water and forested sites (Table S2).

Comparisons between day and night CO_2 concentrations were made for each campaign, per site for the open water habitats, and were statistically different only in the lake site for water-column CO_2 values (paired t test,

351 $t(15)=2.8, p = 0.01$). At this site, mean CO_2 concentration were higher during the
352 night compared to daytime.

353 Temporal and spatial differences in environmental conditions

354 *Environmental conditions at open water sites:* Environmental variables
355 varied with water level. When water depths were shallow (1 to 5 m, low and
356 rising water), Chl-a, TSS, DOC, temperature, DO, pH, underwater attenuation of
357 PAR (K_d) and conductivity were, in general, higher compared to periods with
358 greater water depths (6 to 12 m, high and falling water) (Tables S3 and S4).
359 Chl-a, conductivity and near-surface DO concentrations were, in general, higher
360 in the lake compared with the embayment, although values during high water
361 were similar. In open water in the embayment, vertical gradients in temperature
362 and DO developed during rising and falling water, and resulted in an anoxic
363 hypolimnion during the stratified period. In contrast, in open water in the lake
364 vertical gradients with anoxic hypolimnetic waters were observed only during
365 high water. At both sites, a shallow diurnal thermocline often occurred and
366 varied as a function of wind speed and solar inputs. The wind speeds in the
367 embayment were usually below the threshold of the anemometer ($<0.4 \text{ m s}^{-1}$) at
368 night and early mornings and often higher in early afternoon (0.5 to 2.5 m s^{-1}).
369 In the open lake, wind speeds between 2.5 and 5.0 m s^{-1} were common, and
370 during occasional storms increased briefly up to 10 m s^{-1} . The actively mixing
371 layer was deeper in the open lake compared to the embayment. In the open
372 lake, this region of the upper water column averaged 1.2 and 1.7 m during low
373 and rising water, respectively, and 2.1 and 2.6 m during high and falling water
374 periods. In the embayment, it exceeded 1.0 m (reaching 1.5 m) only during

375 falling water, while during low and high water it averaged 0.6 m, and during
376 rising water averaged 0.9 m.

377 *Inter-annual changes in herbaceous plants:* Areal coverage of
378 herbaceous plants was different in the second year compared to the first year.
379 The areal coverage estimate for the 25 km² quadrant (Fig. 1) in 2016 (0.2 km²)
380 is about one third of the estimate for 2015 (0.6 km²) and half of the area
381 estimated for 2014 (0.4 km²). In the embayment, there were no herbaceous
382 plants present during high and falling water periods at our sampling site in 2016,
383 in contrast to 2014 and 2015.

384 *Diel variations in temperature, DO and CO₂:* Data from September 2015
385 illustrate typical diel variability of temperature, DO and CO₂ concentrations in
386 herbaceous plant mats and open water of the embayment (Fig. 5). As a result of
387 high solar radiation, near-surface water temperature increased rapidly in the
388 mats and in the open water, reaching 40°C in near-surface water within the mat.
389 Near-surface stratification also increased rapidly at both locations.
390 Temperatures were 6 °C warmer in the plant mat than offshore, conditions that
391 are conducive to flow of warmer water to open water (Fig. 6). The vertical
392 temperature gradient was 6 °C over 0.5 m in the plant mat, a condition that also
393 contributed to horizontal temperature gradients. Cooling began as solar
394 radiation decreased, and as a result, temperatures became isothermal in the
395 upper 2 m. A seasonal thermocline was present below 2 m with undulations
396 indicative of internal wave motions at both sites.

397 Dissolved oxygen was elevated with the largest vertical gradients when
398 temperature stratification was strongest. Deeper depths had hypoxic or anoxic
399 water. As the water cooled and stratification weakened, DO declined above the

400 mats but increased mid-water column. The CO₂ profiles illustrate large
401 differences in concentration through the water column, higher values under the
402 mat during the stratified, daytime period, and high values in the upper water
403 during the night in both habitats. The hydrodynamic simulations complement
404 these measurements and illustrate when the patchy increases in concentration
405 result from lateral intrusions (Fig. 6).

406 Hydrodynamic simulations

407 In the embayment, the modeled advection of the tracer away from the
408 floating plants followed a diel cycle in four stages (Fig. 6; Figure S4 and
409 Supplementary Materials): 1) During the first two hours after sunrise (6:00 am to
410 8:00 am), surface water continued to cool and wind speeds were negligible.
411 With near-shore cooling, tracer, which had been added at 0.3 m, descended
412 along the sloping boundary to a depth of 2-3 m. Then, on reaching a depth with
413 comparable density, the tracer flowed offshore. This process is known as
414 differential cooling. 2) From 8:00 am to 5:30 pm, due to the considerable
415 heating of water within the floating plant mats, tracer flowed from the mat to
416 open water in the upper 0.3 m. With the increased stratification, and some wind,
417 a three-layer flow was established, with that near the surface and at 2-3 m
418 flowing offshore with the layer in between flowing in the opposite direction.
419 Modeled results indicate that elevated concentrations of CO₂ could occur in a
420 shallow, surface layer extending 30 to 40 m from the mat. Similarly, a plume
421 with elevated CO₂ was found at 3 m that extended across the embayment. 3)
422 During the hour before sunset (5:00 pm to 6:00 pm), when surface cooling had
423 started and wind speed approached zero, the flow was reversed and, with the
424 decline in the horizontal temperature gradient, the near-surface flow due to

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3 425 differential heating ceased. With cooling causing some mixing near the surface,
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5 426 the surface plume was dispersed. 4) After sunset and before sunrise the
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7 427 following day, cooling eroded the diurnal thermocline. Tracer outside the floating
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9 428 mat was mixed by penetrative convection, while tracer inside the mat again
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11 429 flowed downward and offshore. These descending plumes reached the
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13 430 seasonal thermocline. During these last two time periods, inputs of CO₂ from
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15 431 floating plant mats to open water were reduced near the surface, whereas the
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17 432 plume at ~3 m extended further through the embayment (Fig. S4). Flows such
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19 433 as these explain the intermittent increases of CO₂ observed above the seasonal
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21 434 thermocline in the embayment (Fig. 5).

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25 435 Simulated, near-surface, horizontal velocities within the plant mats were
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27 436 low (Fig. S5; 0.001 to 0.004 m s⁻¹) and are similar to those measured with a
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29 437 warm-bead thermistor flow meter in a similar floating mat by Doyle (1991). In
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31 438 the open water of the embayment, simulated near-surface velocities of 0.01 to
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33 439 0.04 m s⁻¹ were also similar to those measured just outside the mat by Doyle.

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37 440 In the open lake, movement of the tracer, analogous to the movement of
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39 441 CO₂, was moderated by both wind direction, temperature differences and
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41 442 internal wave motions, and exchange between the littoral and pelagic zones
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43 443 occurred at the surface and below with the depth of the flow dependent on wind
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45 444 direction (Fig. 7; Fig. S6). Despite the weak temperature gradient, the water
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47 445 column was stratified. Thus, upwelling of cooler water in the northern basin
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49 446 occurred when winds were northerly or easterly and downwelling when they
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51 447 shifted. Tracer injected along the northern margin during early morning, when
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53 448 temperatures were cooler inshore than offshore, descended during onshore
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55 449 flow and concomitant downwelling conditions. As flow near the surface was
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450 towards the margin, flow in the lower water column was reversed and the plume
 451 moved offshore at depth. Such movement would transfer CO₂ offshore with the
 452 expectation that CO₂ concentrations would increase. Tracer injections when
 453 winds were from the north indicated northerly flow of the plume at the surface
 454 and more limited flow in the lower water column. When southerly winds that had
 455 been sustained for several hours ceased, the thermocline tilted in the opposite
 456 direction as surface water reversed direction. Thus, the tracer plume changed
 457 direction in both surficial and near-bottom waters (Fig. 7b₃, c₃). Hence, potential
 458 inputs of CO₂ from fringing regions are sensitive to wind direction and
 459 associated water motions.

460 Here, we have simulated the pathway of flow from the northern edge.
 461 Given that fringing forest and floating macrophytes occur around the open
 462 water, CO₂ would be expected to be flowing from inshore regions to offshore
 463 from around the lake during the day. At night, the CO₂ which had accumulated
 464 to the upper water would be mixed vertically by penetrative convection.

465 Integration of CO₂ patterns with environmental conditions

466 As the first step in statistical model development, we identified co-linear
 467 variables within the terms of Eq. 1. Actively mixing depth (AMLD) was selected
 468 as the mixing term, as it was shallow in the morning when winds tended to be
 469 light and deepened with increasing wind speed and with cooling at night. Near-
 470 surface CO₂ concentration in herbaceous plant mats (CO₂-MAC), Chl-*a*, and TN
 471 were selected as productivity terms. TP was correlated with TN and, therefore,
 472 not included in the model. Secchi depth was chosen as a proxy of water clarity
 473 as it correlated well with TSS and K_d, but was not correlated with the other
 474 productivity variables. The DOC term included DOC concentration as

quantitative component (no correlations with CDOM - quality proxies), and SR as a DOC-quality variable, since it correlated or marginally correlated with the other CDOM parameters (SUVA and a_{350}). There was no correlation between variables representative of the inundation term, so both ΔZ and the open water to flooded forested area ratio (OW:forest area) were included in the model. Finally, temperature was chosen, as it correlates with specific conductance, an indicator of river or stream water, to represent the term called other.

The full model started with the ten selected variables, but OW:forest area and temperature were excluded from the model after the VIF correlation test. CO_2 -MAC, Chl-a, Secchi depth and ΔZ were selected and distributed into three best models within 2.0 AIC units from the best model. The magnitude of the effect that each variable had on water-column CO_2 concentrations indicates that CO_2 -MAC is the variable with the highest estimate followed by Secchi depth, ΔZ and Chl-a (Fig. 8). Hence, Eq. 1 can be re-written including variables present in the best models with their respective estimators:

$$Eq\ 2: CO_2 = \alpha + 0.18 \Delta Z - 0.19Chla + 0.33Secchi + 0.69CO_2MAC.$$

Discussion

Our findings elaborate and extend understanding of CO_2 in tropical lakes and floodplains with measurements and models covering the four hydrological phases. Measurements were obtained over diel cycles and in open water and vegetated habitats. The best statistical model of water-column CO_2 concentrations included terms representing inundation (ΔZ) and three terms related to primary productivity (planktonic chlorophyll *a*, CO_2 associated with herbaceous plant mats, and transparency as indicated by Secchi depth). CO_2

associated with herbaceous plant mats had the strongest positive influence, while planktonic chlorophyll was less important and had a negative effect. While the statistical model considered several factors related to changes in CO₂ concentrations, the terms used to represent the factors do not include all the processes. Hence, other ecological and biogeochemical processes based on relevant literature are combined with discussion of our results. The hydrodynamic modeling enhances understanding of specific physical processes influencing CO₂ dynamics. As will be discussed below, our observations provide a new perspective on the active pipe hypothesis.

Herbaceous plants as a source of CO₂ to open waters in floodplain lakes

In Amazon floodplain lakes, a significant amount of CO₂ is derived from vegetated aquatic habitats and is transported by physical processes into open waters. This result contrasts with the emphasis on the supply and processing of terrestrial inputs by lakes and rivers as conceptualized and quantified in numerous lakes by the active pipe hypothesis (Cole and others 2007), suggested by Richey and others (2002) for the Amazon basin and incorporated into models of Amazon carbon cycling (Lauerwald and others 2017). The floating mats of herbaceous plants commonly found in Amazon floodplain lakes are predominantly highly productive C₄ grasses (Piedade and others 1991; Junk and Piedade 1993; Engle and others 2008). These plants obtain CO₂ from the atmosphere and add almost all their organic carbon to the water during an annual growth and decomposition cycle. Engle and others (2008) estimated that loss rates per month of above- and below-water biomass ranged from 31% to 75%, amounting to 30 to 34 gC m⁻² d⁻¹. Almost all the carbon in this plant

524 biomass is decomposed rapidly in the water and surficial sediments (Furch and
525 Junk 1997; Mortillaro and others 2016) releasing dissolved CO₂ and CH₄.

526 Results from stable isotopic analyses support the idea of the importance
527 of herbaceous aquatic plants to CO₂ concentrations in floodplain lakes. Quay
528 and others (1992) evaluated $\delta^{13}\text{C}$ values in different C fractions sampled on an
529 1800 km transect along the Solimões/Amazon River, including its main
530 tributaries and a few floodplain sites, and suggested that about 40% of the
531 respired organic carbon was derived from C4 herbaceous plants. In a central
532 Amazon floodplain lake, Waichman (1996) compared the $\delta^{13}\text{C}$ value of CO₂
533 produced by bacterioplankton, incubated in filtered water sampled from open
534 water, flooded forest and floating meadows to the plants in an Amazon
535 floodplain lake in order to identify the autotrophic carbon source for these
536 organisms. She found good agreement between the $\delta^{13}\text{C}$ values of the CO₂
537 produced and that of C4 herbaceous plants and concluded that
538 bacterioplankton living in floating plant mats and flooded forests derived 90% of
539 their carbon from C4 plants while those in open water environments derived
540 73% of their carbon from this source.

541 Respiration by the submerged roots and the periphyton community
542 associated with the roots likely contribute to the high CO₂ concentrations within
543 floating plant mats. The upper 0.5 m or so under floating plants is a mixture of
544 roots, stems and leaves, all of which are substrata for epiphytic bacteria, algae
545 and a diverse epifauna (Engle and Melack 1989). For example, in floating
546 *Paspalum repens* mats in a central Amazon floodplain lake the roots
547 represented approximately 11 to 48 gC m⁻², and attached periphyton 8.0 to 17
548 gC m⁻² over a growing season (Engle and Melack 1993). Moreover, the organic

549 matter produced by the periphyton is of higher quality for grazers than the plant
550 material.

551 Doyle (1991) measured rates of photosynthesis and respiration of
552 periphyton and associated roots in chambers deployed in situ with natural light
553 and flow conditions. Autotrophic growth was limited to a shallow euphotic zone
554 (often < 0.2 m). Doyle estimated the portion of respiration by root tissue to vary
555 from 5.0 to 25% of the total respiration of the root plus periphyton depending on
556 the size and colonization of the roots. To convert dissolved oxygen-based
557 measurements of respiration to carbon, Doyle determined the ratio of moles of
558 CO₂ produced to moles of O₂ consumed to be 0.8. Monthly rates of respiration,
559 using his preferred extrapolation method, were calculated to vary from
560 approximately 2.0 to 59 gC m⁻² month⁻¹ with an average of 33 gC m⁻² month⁻¹. If
561 converted to a daily rate and distributed in the upper 0.5 m of water, an average
562 daily increase in CO₂ of about 200 µM would result. Another estimate of the
563 total respiration associated with *P. repens* roots and periphyton is indicated by
564 the night-time decline of DO within bags with a root cluster and periphyton from
565 an average of 3.4 mg L⁻¹ to 1.2 mg L⁻¹ (Engle and Melack 1993). If converted to
566 CO₂ using Doyle's ratio, 55 µM would be produced during the night.

567 Our measurements, statistical analysis and hydrodynamic modeling
568 indicate that waters with elevated concentrations of dissolved gases can be
569 mixed or advected from vegetated habitats to open water. Several physical
570 processes can cause lateral and vertical motions that can link benthic, pelagic
571 and littoral habitats (MacIntyre and Melack 1995). Floating mats of vascular
572 plants can reduce solar radiation reaching into the water, resulting in cooler
573 water under the mats but warmer near-surface water compared to open water

and causing temperatures differentials and advective motions (Coates and Ferris 1994). As solar radiation declines in the day and is absent at night, water near the surface cools inducing vertical mixing of the water column by penetrative convection (Augusto-Silva and others 2019). This mixing brings dissolved gases which had been transported at depth by differential cooling in embayments (Fig. 6) to the surface where they can evade to the atmosphere.

In open waters, stratification supports internal waves such that the thermocline up- and down-wells with changes in wind speed and direction. These processes can bring high concentrations of CO₂ offshore to near the surface when winds flow offshore and to the lower water column when winds flow onshore. The circulation within the downwelled mixed layer is similar to that described by Mortimer (1952) in that surface water flows towards shore and that of the base of the mixed layer flows offshore. Thus, internal wave mediated flows transport dissolved gases either offshore near the surface or onshore to the lower water column. Nocturnal cooling or strong wind events can entrain waters with higher CO₂ concentrations from the lower water column increasing values in the upper water. When concentrations of CO₂ are elevated near the surface, evasion to the atmosphere is enhanced (Amaral and others 2020).

Interannual variations of herbaceous plants and impacts on CO₂ concentrations

Year to year differences in plant growth and decay moderates CO₂ concentrations. These processes depend on the duration of low water. Higher CO₂ concentrations were observed in high and falling periods of the first year compared to the second year of our study (Fig. 4). Exceptionally low water levels in 2015, caused by a regional, extended drought, possibly related to an El Niño event (Jiménez-Muñoz and others 2016), led to the mortality of floating

599 *Paspalum repens* mats, and the emergence of large areas of exposed lake
600 bottom on which *Luziola spruceana* and *Oryza rufipogon* grew (Amaral and
601 others 2018; Rodrigo Nunes, personal communication). When water levels rose
602 in January and February 2016, these areas were inundated, and *L. spruceana*
603 senesced and decomposed. When water levels reached ~5 m (March-April), *O.*
604 *rufipogon* also senesced and decomposed. The mortality and decomposition of
605 these plants were likely the cause of higher CO₂ during the rising water of year
606 two compared to the year one, at both sites, as well as the atypically high CO₂
607 in the embayment during the low water period of year two (Table 1 and Table
608 S1). Few floating plants occurred during the high and falling periods of 2016 in
609 the embayment, which may have contributed to the lower CO₂ values in the
610 embayment during these periods when compared to similar periods in 2015,
611 when floating plants were present (Fig. 4). Areal coverage of floating
612 herbaceous plant estimated by remote sensing for the 25 km² quadrant in 2016
613 was one third of the estimate for a similar period in 2015.

614 615 Variations in environmental conditions, their impact on CO₂ concentrations and 616 alternative sources of CO₂ in floodplain lakes

617 In open waters, especially during low water, high chlorophyll-*a*
618 concentrations are often observed in Amazon floodplain lakes (Tables S3 and
619 S4; Barbosa and others 2010; Forsberg and others 2017a). The higher diel CV
620 of CO₂ concentrations recorded during rising and low water is likely related to
621 diel variations in plankton metabolism. Occasionally, under-saturation of CO₂
622 can occur in Amazon floodplain lakes during periods with abundant
623 phytoplankton during daytime (Abril and others 2014; Amaral and others 2018).

At night, CO₂ concentrations increase due to plankton respiration. These dynamics are evident in the day-night differences observed in the open lake. The inverse relationship between Chl-a and CO₂ concentrations, represented in the statistical model (Eq. 2), and commonly associated with pelagic primary production is likely to be the cause of lower CO₂ during the low and rising water period.

Several other variables were important in the model. Secchi depth was a positive term in the model. Reduced transparency is associated with sediment suspension during periods of low water and river inflows, and with abundant phytoplankton, especially in the open lake, that led to reduced CO₂. Conversely, increases in water transparency and water-column CO₂ in the embayment are likely related to stratified conditions, as CO₂ accumulated below the seasonal thermocline. Amaral and others (2018) provide an example of higher CO₂ concentrations in deeper water compared to upper water in both the main lake and embayment during a stratified period. During periods of falling water levels, as indicated by Δz , CO₂ enriched waters from the hypolimnion are likely to mix through the water column.

To further examine the relations between CO₂ concentrations and vertical mixing, we compared the ratio between near-surface and water column averaged CO₂ concentrations and the depth of the actively mixing layer. As mixing increased, differences between near-surface and water column averaged CO₂ concentrations, decreased, i.e., increased vertical mixing reduced vertical variability of CO₂ concentrations.

The metabolism of the plankton community is another source of variability in CO₂ concentrations in Amazon floodplain lakes (Richey and others

1988). Amaral and others (2018) reported rates of plankton respiration in Lake Janauacá of $97 \mu\text{moles CO}_2 \text{ L}^{-1} \text{ d}^{-1}$ in the lake and $56 \mu\text{moles CO}_2 \text{ L}^{-1} \text{ d}^{-1}$ in the embayment. Methane oxidation is also a planktonic source of CO_2 ; based on average rates of methane oxidation in Lake Janauacá, $\sim 2.0 \mu\text{moles CO}_2 \text{ L}^{-1} \text{ d}^{-1}$ could be generated (Barbosa and others 2018).

The sediments of floodplain lakes sequester some organic carbon and release CO_2 to the overlying water as a portion of the sedimented carbon is metabolized (Smith and others 2003). Using a simple model of diagenesis for two small Amazon lakes, Devol and others (1984) estimated 6.0 and $24 \text{ mmol m}^{-2} \text{ d}^{-1}$ of carbon was oxidized. Using submerged chambers, Smith-Morrill (1987) measured dissolved oxygen uptake during periods when the near-bottom waters were aerobic of $\sim 50 \text{ mmol m}^{-2} \text{ d}^{-1}$. Under stratified conditions with anoxic bottom waters, carbon efflux from sediments estimated from efflux of ammonium and the C:N ratio in the sediments varied from 55 to $\sim 200 \text{ mmol m}^{-2} \text{ d}^{-1}$.

CO_2 concentration is known to co-vary with DOC concentration across different lakes (Sobek and others 2005; Lapierre and del Giorgio, 2012), and the relation is often interpreted to result from inter-lake variations in allochthonous organic and possibly simultaneous inorganic carbon inputs. However, within our single system (Lake Janauacá), we did not find a significant correlation between CO_2 and DOC concentrations (Pearson's correlation $p=0.15$, $r^2=0.06$). This was consistent with the results of Waichmann (1996) who found the CO_2 liberated by bacterioplankton and the measurable DOC pool to be isotopically distinct. She suggested that two DOC pools existed in this system, a labile pool derived predominantly from C_4 plants that is rapidly

transformed into CO₂ and a more refractory pool derived predominantly from C3 plants that accumulates in the water column. That SUVA, an indicator of CDOM aromaticity, often associated with refractory terrestrial carbon (Weishaar and others 2003), was negatively correlated with CO₂ concentrations ($p=0.12$, $r^2=-0.29$) supports this argument. The highest SUVA values (> 5) occurred during low and rising water periods (Fig. S1), when waters on the floodplain contain relatively more water from their local drainage (Bonnet and others 2017). Furthermore, DOC in dry soils is likely to be mobilized by inundation (Melo and others 2019; Silva and others 2020), leading to high SUVA values measured during rising water. SR, with lower values indicating a CDOM of high molecular weight (Helms and others 2008), likely associated with DOC of terrestrial origin, had the lowest values during high water (Fig. S1), and was low during early rising water. The CDOM parameters suggest a period of relatively high terrestrial inputs during early rising water, and of the importance of inputs during higher water periods. This inference is supported by CDOM parallel factor analysis (Melo and others 2019). Further research is needed to evaluate the importance of terrestrial inputs and possible priming effects on DOC removal and CO₂ production in floodplain lakes (Ward and others 2016).

In addition to movements of CO₂ within the Janauacá floodplain, inputs of water from local seepage and runoff and the Solimões River can introduce CO₂ and influence the variations in concentration observed. A water balance model and tracing of water with electrical conductance by Bonnet and others (2017) demonstrated large spatial and seasonal variations in the contributions of water from the different sources, and a water retention time in the lake from 27 to 71 days. Further evidence of the complexity of the water motions is provided by an

699 application of a 2-dimensional hydrological-hydrodynamic model that revealed
700 heterogeneities in water velocities throughout the floodplain and how inputs
701 from the Solimões River and local runoff influenced circulation patterns within
702 the lake (Pinel and others 2020). During our study, concentrations of CO₂ in
703 water at the southern end of the lake, at times with strong influence by local
704 runoff and seepage, averaged 175 µM, and in the channel linking the lake to the
705 Solimões River averaged 88 µM during periods of inflow with low floodplain
706 influence. These values are less than most values measured in herbaceous
707 plant mats and flooded forests, reinforcing the importance of aquatic vegetative
708 habitats as sources of dissolved CO₂, in relation to other potential sources on
709 the floodplain.

710 Implications associated with environmental changes

711 Major changes in the discharge and flooding patterns of Amazon
712 tributaries during the next 50 years are predicted due to anthropogenic climate
713 change, with shallower water and reductions in inundation extent expected for
714 most of the central Amazon (Sorribas and others 2016). Our study indicates
715 likely expected outcomes. When exposed, lake sediments favor growth of
716 herbaceous plants and when flooded by rising water, the plants decay and
717 release CO₂ that can be emitted to the atmosphere. Our observations of DO
718 depletion when the herbaceous plants were flooded and decaying support this
719 interpretation. Furthermore, CH₄ concentrations in open waters of the Janauacá
720 floodplain at this time were nearly 10 times higher than concentrations
721 measured during the previous year during rising water (Barbosa and others
722 2020). Thus, multiple lines of evidence point to increased concentrations of CO₂
723 during rising water under regional droughts.

724 A complex set of metabolic pathways would moderate the carbon
725 balance during extended low water periods on floodplains. Although CO₂
726 concentrations and outgassing rates can increase as a result of the decay of
727 inundated rooted herbaceous plants, this carbon is likely to be largely balanced
728 by photosynthetic uptake by these plants (Amaral and others 2018). However,
729 since a portion of this organic carbon is transformed to CH₄, the emission of
730 CH₄ will contribute to atmospheric warming. In addition, the conditions
731 observed during the extended low water period emphasize the importance of
732 the aquatic-terrestrial transition zone to the production and fate of organic
733 matter (Kayler and others 2019).

734 The absence of floating herbaceous plants in the embayment during the
735 high and falling water period of 2016 is likely associated with fires set by local
736 residents during the prolonged low water period in early 2016. The fires may
737 have affected the seed bank of *Paspalum repens*. Management actions should
738 attempt to reduce the impact of slash and burn practices, especially under
739 drought and extended low water conditions in order to preserve herbaceous and
740 forest habitats. These conditions would also favor loss of sediments to the river,
741 especially in floodplain areas that are susceptible to turbulence and water
742 currents, with the potential to affect the establishment and regrowth of
743 herbaceous species in these areas (Piedade and others 2010). The reduced
744 presence of *P. repens* may also reflect the direct negative impact of the
745 prolonged low water period on seed and rhizome survival, an effect which is
746 expected to worsen with anthropogenic climate change (Sorribas and others
747 2016).

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748 The building of dams on large Andean tributaries of the Amazon River
749 will cause changes that may further moderate the carbon balance in the
750 floodplain. The potential impacts of these dams include reduced supplies of
751 sediments, phosphorus and nitrogen to the lowland floodplains, with probable
752 negative consequences for aquatic productivity, and changes in the timing and
753 magnitude of seasonal flooding below dams which is expected to degrade
754 flooded forests (Forsberg and others 2017b). These changes will modify the
755 concentrations and emissions of CO₂ in floodplain environments. Strategic,
756 basin-wide planning and the use of alternative energy sources could optimize
757 energy production and minimize environmental impacts (Almeida and others
758 2019).

759 **Conclusions**

760 We demonstrated metabolic processes in floating herbaceous plants are
761 a key driver of CO₂ variability in Amazonian floodplains. The influence of
762 floating herbaceous plants exceeded that from changes in water level, pointing
763 to within lake processes modifying the active pipe hypothesis. That is,
764 respiration, production and decay of these plants was a major contributor to
765 concentrations of CO₂, more so than water flowing in from the river or
766 catchment. Physical processes transferred the CO₂ produced in near-shore
767 regions to offshore locations with greater wind exposure where rates of evasion
768 could be more rapid. We also found consistent differences in CO₂ dynamics
769 between embayments and open lake portions of a floodplain system. In short,
770 we have provided evidence for 1) aquatic herbaceous plants fringing floodplain
771 lakes as sources of dissolved CO₂ to the open waters, 2) that CO₂
772 concentrations are higher in embayments particularly when stratified during high

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3 773 water in comparison with to an open lake where mixing penetrated to deeper
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5 774 depth and facilitated evasion, thus water column stratification and mixing are a
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7 775 source of CO₂ variability: 3) that diel differences in stratification and lateral
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9 776 movements of water alter CO₂ concentrations and can increase concentrations
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11 777 offshore; 4) that CO₂ concentrations were higher during periods with deeper
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13 778 water and larger areas of inundation, 5) that inter-annual differences in CO₂
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15 779 concentrations were associated with changes in abundance of herbaceous
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17 780 plants and were affected by extended low water periods, and 6) how seasonally
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19 781 changing water levels and transparency interact with vertical mixing to alter
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21 782 CO₂. Our statistical model successfully incorporated variables to represent
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23 783 vegetation, inundation, and vertical mixing as sources of variability in CO₂
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25 784 concentrations.
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For Peer Review

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1048 **Table 1**

Site		CO ₂ Water- Column (µM)							
		Open water				Herbaceous plants			
		LW	RW	HW	FW	LW	RW	HW	FW
Open lake	Median	4,17	156,34	249,20	185,33	n.d	234,30	277,17	243,9
	Mean	11±14	146±71	245±46	190±54	n.d	248±82	271±42	236±73
	Range	0.2/ 46	3.8/ 255	135/ 302	70/ 298	n.d	25 / 370	205 / 373	134 / 352
Embayment	Median	205,13	288,45	330,23	275,21	185,7	280,34	342,9	352,9
	Mean	168±119	313±89	351±46	226±144	180±55	304±64	345±27	311±89
	Range	4/ 352	192/ 485	249/ 452	11/ 428	91/ 256	226 / 450	306 / 389	169 / 396

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1050 **Table Legend**

1051 Table 1. Median and number of observations, mean and (±) standard
 1052 deviation, maximum and minimum water-column CO₂ concentrations (µM) in
 1053 open water and herbaceous plant habitats in L. Janauacá at each site during
 1054 low water (LW), rising water (RW), high water (HW) and falling water (FW).

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Figure Legends

Figure 1. Lake Janauacá on the Solimões River floodplain. Upper panel. A: approximate locations of open lake sampling sites (OL) during high water (HW) and low water (LW). B: embayment site (EM) and reference quadrant (25 km²), used for estimate of areal coverage of herbaceous aquatic plants. Lower images are detailed views of habitats A and A.1 (OL site): open water at HW (yellow square), flooded forest (yellow triangle) and floating plants (yellow circle). B (EM site): open water (red square), flooded forest (red triangle) and floating plants (red circle). Multispectral images: Upper and A: Planet Scope Rapid-eye image acquired on 08/15/2015; A.1 and B: Apollo World View -2 image on 08/14/2014.

Figure 2. Measurement dates in open water (square), flooded forest (triangle) and floating herbaceous plant (circle) habitats and water depths at open water locations in lake and embayment from August 2014 to September 2016. Dashed lines separate hydrological years.

Figure 3. Differences between near-surface and water-column CO₂ concentrations measured at open water sites in embayment (left) and lake (right) in L. Janauacá. 1:1 line is dashed line.

Figure 4. Water-column CO₂ concentrations for the (A) open water habitat, and (B) all habitats (forest, herbaceous plants and open water) combined during low water (LW), rising water (RW), high water (HW) and falling water (FW) of year one (2014-2015) black circles and year two (2015-2016) open circles. Dots

1084 represent mean values and error bars the standard deviations of the mean
 1085 values

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1087 Figure 5. Diel variations during falling water (September 2015) in herbaceous
 1088 plant mats (left) and open water (right) of embayment of L. Janauacá.
 1089 Photosynthetically active radiation (PAR, a), surface temperature (0.05 m) (b),
 1090 CO₂ (c) and dissolved oxygen (d) contours (colors) with white dots representing
 1091 depths of measurements of CO₂ and position of dissolved oxygen sensors;
 1092 black lines are isotherms based on thermistors (spaced 0.3 to 0.5 m over the
 1093 top 2 m and 0.5 to 1 m over the other depths).

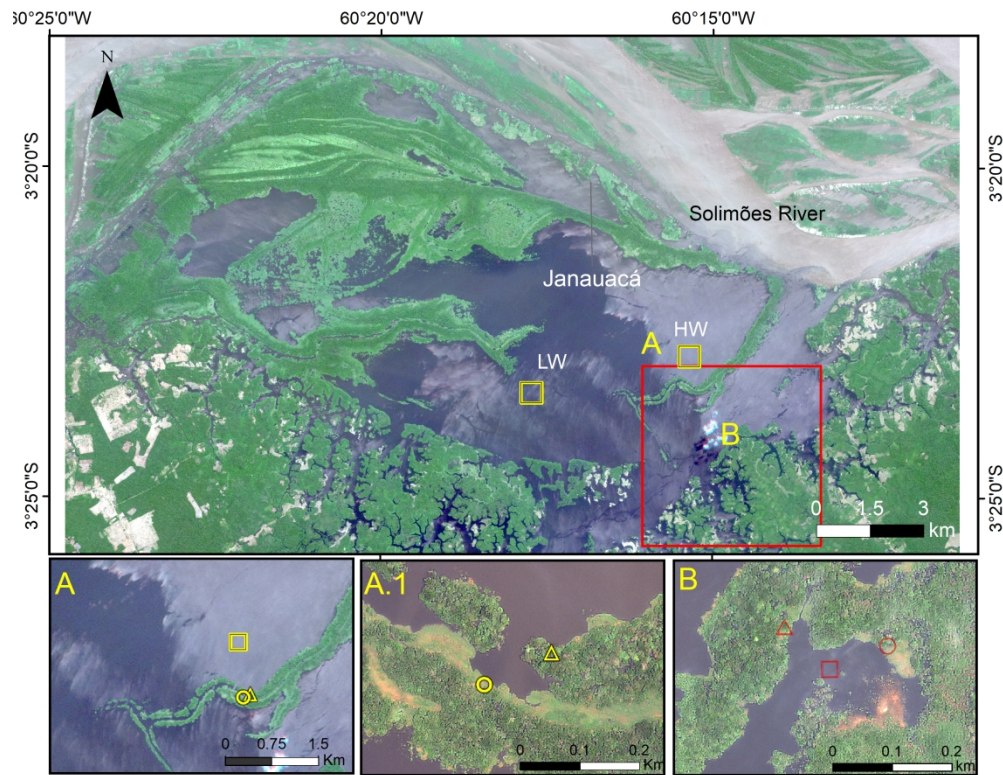
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1095 Figure 6. Cross sections illustrating hydrodynamic simulations over a diel cycle
 1096 for the embayment. Wind speed and net surface heat flux (a) and snapshots of
 1097 AEM3D simulated vertical profiles of temperature (b₁ to b₄) and tracer
 1098 expressed as CO₂ concentrations (c₁ to c₄) at FB at four different times marked
 1099 by the numbered dash-dot lines in panel a. The black dashed lines mark the
 1100 extent of the plant mat.

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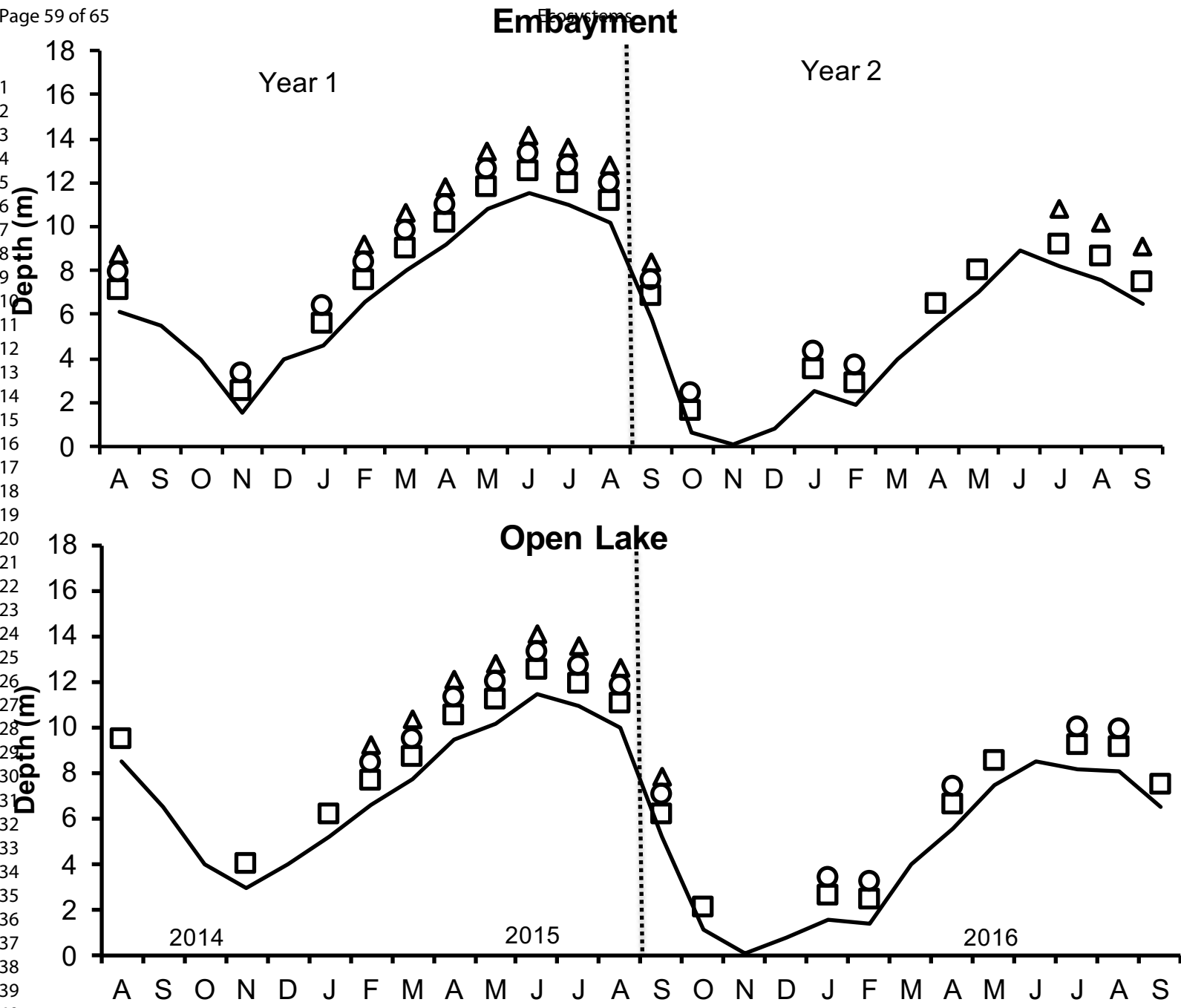
1102 Figure 7. Hydrodynamic simulations for open lake illustrating movements of a
 1103 plume of tracer as CO₂ viewed in plane-view at two depths. Meteorological
 1104 conditions and water level as measured in August 2016. Wind speed and net
 1105 surface heat flux indicating surface heating and cooling (a). Simulated tracer as
 1106 CO₂ concentration across the domain at surface (b₁ to b₃) and 5.0 m (c₁ to c₃) at
 1107 DOY 235.58, 236.672 and 238.65. White lines in each contour are the

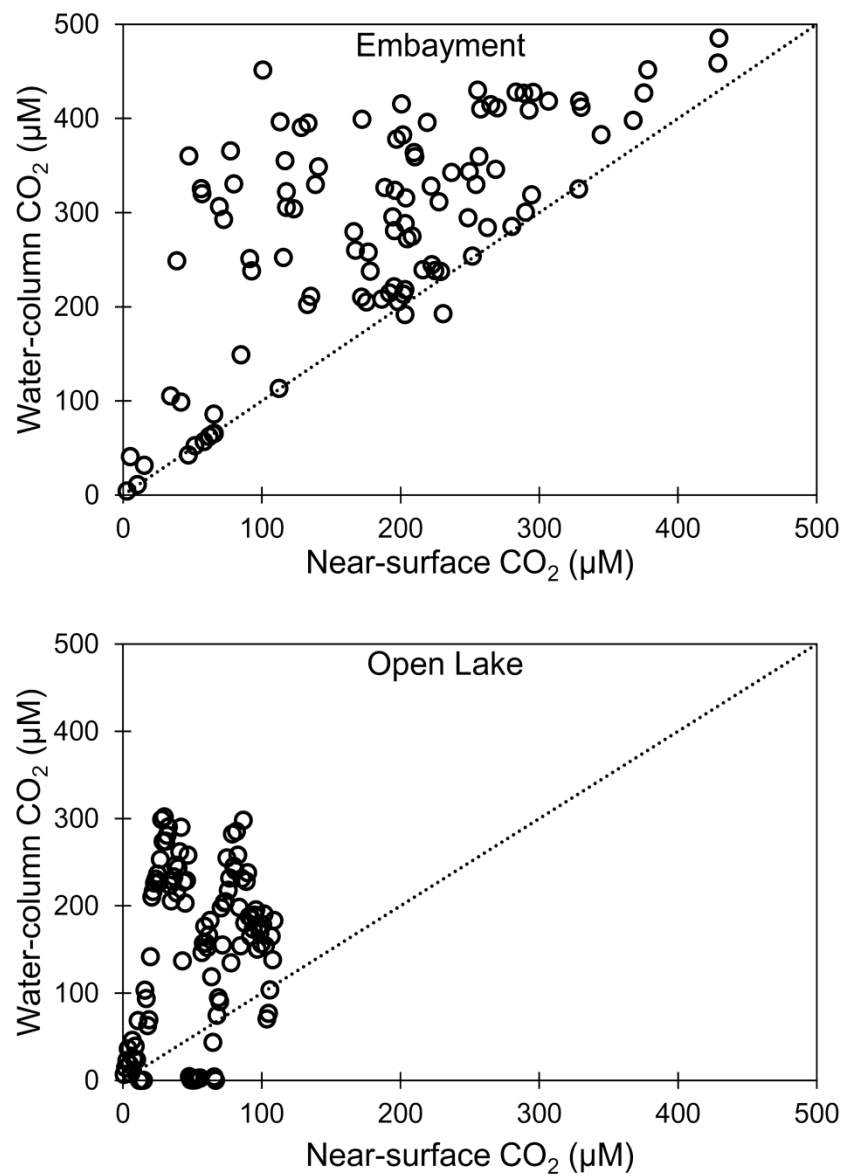
1
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3 1108 isotherms spaced at 0.5°C. Arrows and circles at the lower right corner of the
4
5 1109 surface panels show the wind direction and speed.
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7 1110
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9
10 1111 Figure 8. Estimates for regression slopes ($\pm$ 95% confidence intervals, CIs)
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12 1112 showing the magnitude and direction of the effects of different variables on
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14 1113 water-column CO₂ concentrations within the eleven campaigns sampled
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16 1114 between November 2014 and October 2015 on the Janauacá floodplain. Solid
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18 1115 circles indicate the mean estimates and horizontal lines indicate confidence
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20 1116 intervals. For significant variables, CIs do not cross the dotted line at zero.
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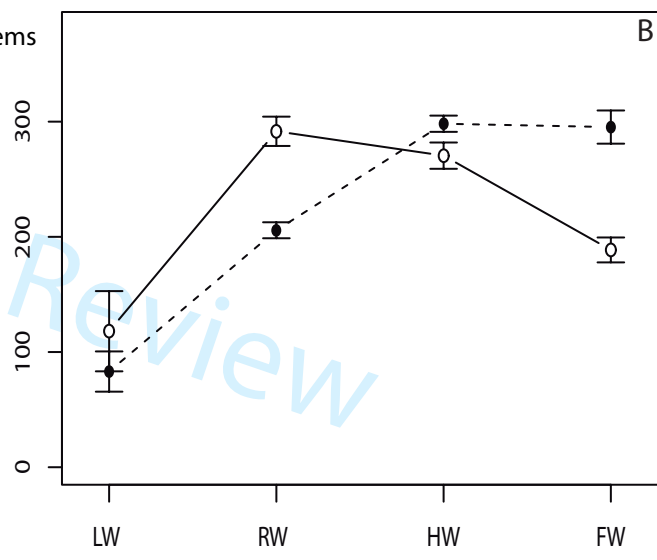
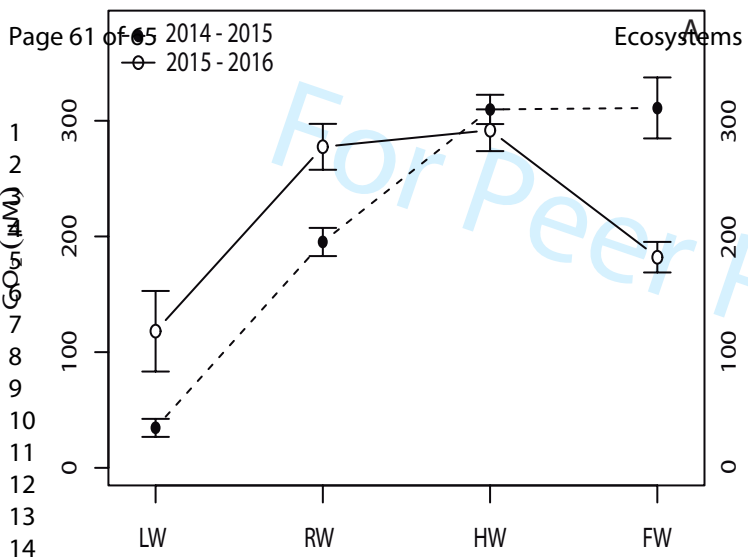
Lake Janauacá on the Solimões River floodplain. Upper panel. A: approximate locations of open lake sampling sites (OL) during high water (HW) and low water (LW). B: embayment site (EM) and reference quadrant (25 km²), used for estimate of areal coverage of herbaceous aquatic plants. Lower images are detailed views of habitats A and A.1 (OL site): open water at HW (yellow square), flooded forest (yellow triangle) and floating plants (yellow circle). B (EM site): open water (red square), flooded forest (red triangle) and floating plants (red circle). Multispectral images: Upper and A: Planet Scope Rapid-eye image acquired on 08/15/2015; A.1 and B: Apollo World View -2 image on 08/14/2014.

279x215mm (300 x 300 DPI)

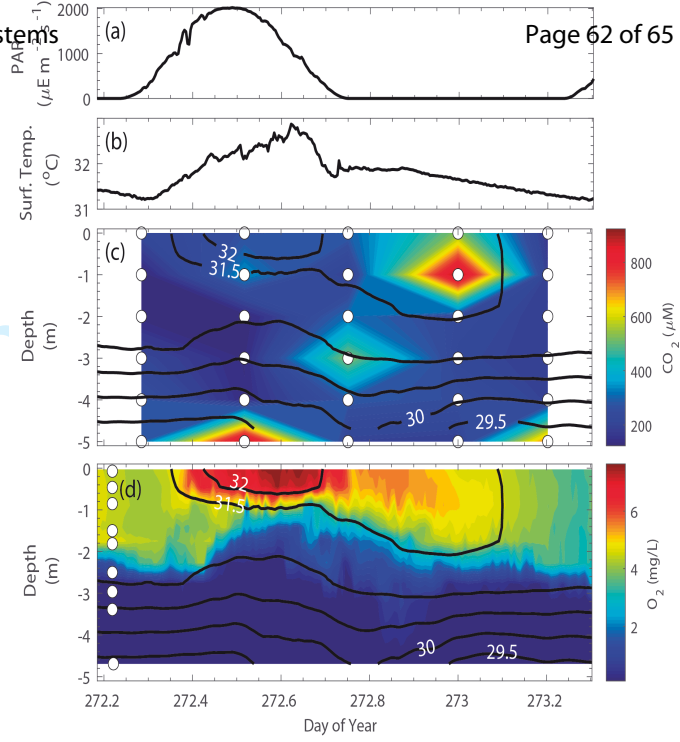
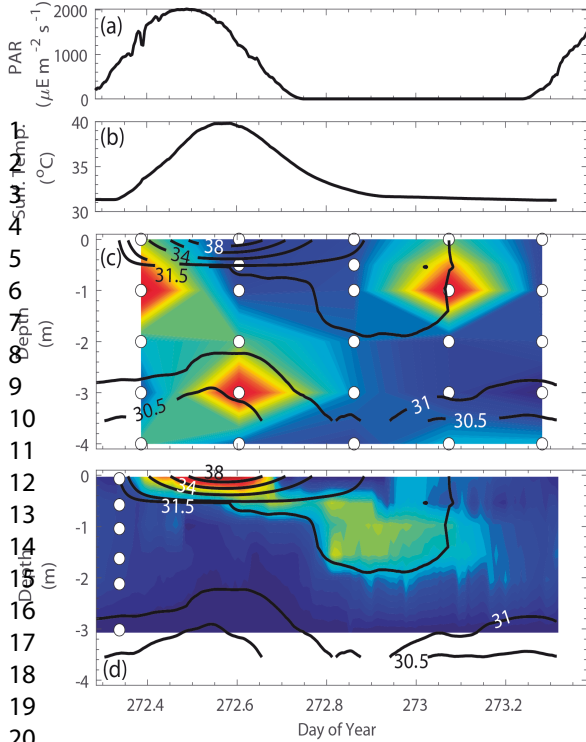


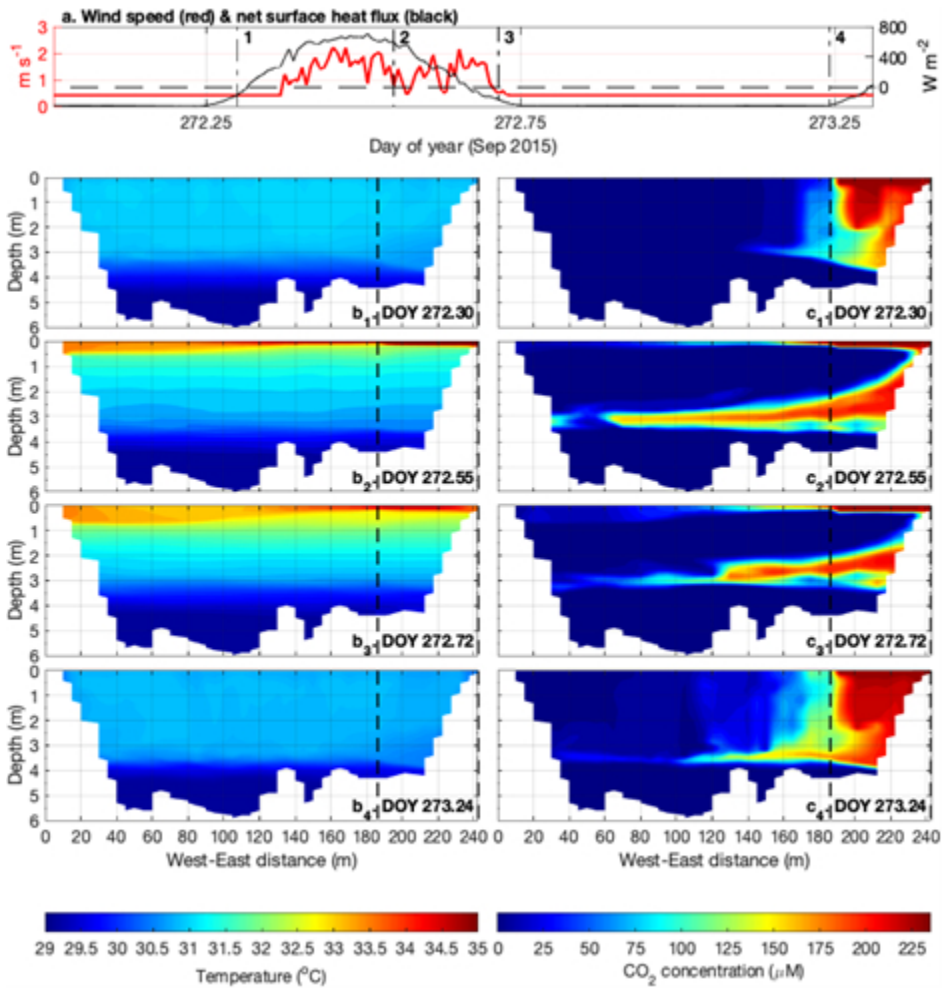


Differences between near-surface and water-column CO₂ concentrations measured at open water sites in embayment (left) and lake (right) in L. Janauacá; 1:1 line is dashed line.



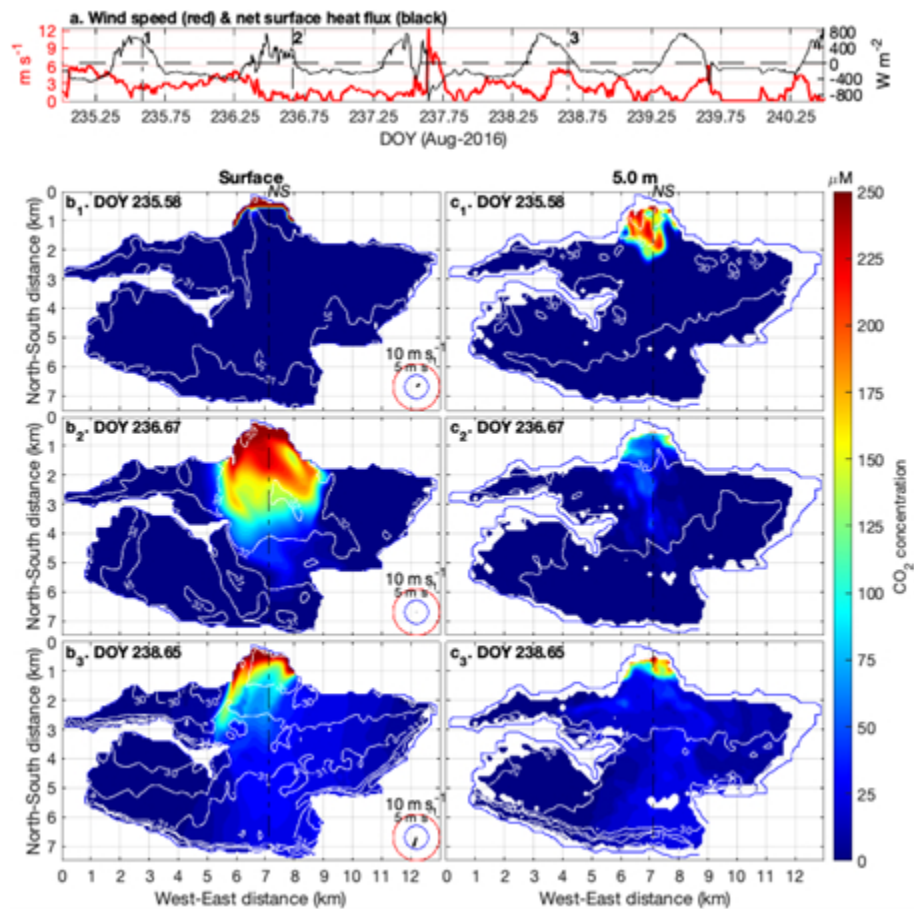
Ecosystems





Cross sections illustrating hydrodynamic simulations over a diel cycle for the embayment. Wind speed and net surface heat flux (a) and snapshots of AEM3D simulated vertical profiles of temperature (b1 to b4) and tracer expressed as CO₂ concentrations (c1 to c4) at FB at four different times marked by the numbered dash-dot lines in panel a. The black dashed lines mark the extent of the plant mat.

165x172mm (72 x 72 DPI)



Hydrodynamic simulations for open lake illustrating movements of a plume of tracer as CO_2 viewed in plane-view at two depths. Meteorological conditions and water level as measured in August 2016. Wind speed and net surface heat flux indicating surface heating and cooling (a). Simulated tracer as CO_2 concentration across the domain at surface (b_1 to b_3) and 5.0 m (c_1 to c_3) at DOY 235.58, 236.672 and 238.65. White lines in each contour are the isotherms spaced at 0.5°C . Arrows and circles at the lower right corner of the surface panels show the wind direction and speed.

159x158mm (72 x 72 DPI)

Secchi depth

CO₂ MAC

Chl-a

 ΔZ

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Estimate

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Variable

